

Pentaquark Search with Energetic Hadron Beams

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Abstract

The strange-anticharmed Pentaquark is a $uud\bar{c}s$ or $udd\bar{c}s$ five-quark baryon that is expected to be either a narrow resonance, or possibly even stable against strong decay. We describe this hyperon here; its structure, binding energy and lifetime, resonance width, production mechanisms and decay modes. We estimate production cross sections, techniques to reduce backgrounds in search experiments, and how to optimize experiments to observe it. Possibilities for enhancing the signal over background in Pentaquark searches are investigated by examining predictions for detailed momentum and angular distributions in multiparticle final states. General model-independent predictions are presented as well as those from two models: a loosely bound $D_s^- N$ "deuteron" and a strongly-bound five-quark model. Fermilab E791 data, currently being analysed, may be marginal for showing definitive signals. Future experiments with more than 10^5 reconstructed charmed baryon events should have sensitivity to determine whether or not the Pentaquark exists.

1 Introduction

Ordinary hadrons are mesons or baryons, whose quantum numbers can be described by quark-antiquark or three-quark configurations. Unusual hadrons that do not fit this picture would constitute new forms of hadronic matter - exotic hadrons. Such hadrons may have significant multi-quark configurations such as $qq\bar{q}\bar{q}$ and $qqqq\bar{q}$. Exotic hadrons can have anomalous quantum numbers not accessible to a three-quark or quark-antiquark structures (open exotic states) or even usual quantum numbers (cryptoexotic states). Cryptoexotic hadrons can be identified only by their unusual dynamical properties (anomalously narrow decay widths, anomalous decay branching ratios, etc.). The discovery of exotic hadrons would have far-reaching consequences for quantum chromodynamics, for the concept of confinement, and for specific models of hadron structure (lattice, string and bag models). Detailed discussions of exotic hadron physics can be found in recent reviews [1].

We consider here possible exotic hadronic states with heavy quarks (c, b), which contain quarks with four different flavors (e.g. u, d, s, c). Their properties follow from the general hypothesis of "flavor antisymmetry" [2], by which quark systems characterized by the maximum possible antisymmetry of quark flavors (both quarks and antiquarks) are the most strongly bound. For instance, this means that the $uud\bar{s}$ system would be more bound than the $uud\bar{s}$ one, etc.

Jaffe [3] predicted in this spirit that for dibaryons with six light quarks, the most bound is the Hexaquark $H = [u,u,d,d,s,s]$ combination, for which not more than two quarks are in states with identical flavors. Lipkin [4] and Gignoux *et al.* [5] showed that 5-quark "anticharmed" baryons (Pentaquarks) of the $P^0 = [uud\bar{c}s]$ and $P^- = [udd\bar{c}s]$ type, or analogous "anti-beauty" baryons, are most bound in the 5-quark sector. There are also predictions [6] for the most bound tetraquark exotic meson, the $\tilde{F}_s = [cs\bar{u}\bar{d}]$.

2 Binding Energy of the Pentaquark

Some of these exotic states with heavy quarks may be bound. The masses would be below the threshold for strong decays (i.e., $M(P^0) < M(D_s^-) + M(p)$). Such quasi-stable bound states would decay only via weak interactions, with typical weak decay lifetimes. Resonant states with masses above the strong decay threshold would decay strongly. In the present work, we focus on experimental searches for the Pentaquark, both bound and resonant varieties.

The binding potential of a system is given by the difference between the Color Hyperfine CH interaction in the system and in the lightest color-singlet combination of quarks into which it can be decomposed. The wave function of the H may be written as:

$$\Psi_H = \alpha_1 \Psi_{6q} + \beta_1 \Psi_{(\Lambda\Lambda)} + \gamma_1 \Psi_{(\Sigma^-\Sigma^+)} + \delta_1 \Psi_{(\Xi^-p)}. \quad (1)$$

The lightest color singlet combination is the $\Lambda\Lambda$ system at 2231 MeV. The CH contribution to the binding energy of the H is about 150 MeV, in simple models of the CH interaction. Similarly, the P^0 and P^- wave functions can be written as:

$$\Psi_{P^0} = \alpha_2 \Psi_{5q} + \beta_2 \Psi_{(D_s^-p)} + \gamma_2 \Psi_{(\Sigma^+D^-)} + \delta_2 \Psi_{(\Lambda\bar{D}^0)}, \quad (2)$$

$$\Psi_{P^-} = \alpha_3 \Psi_{5q} + \beta_3 \Psi_{(D_s^-n)} + \gamma_3 \Psi_{(\Sigma^-\bar{D}^0)} + \delta_3 \Psi_{(\Lambda D^-)}. \quad (3)$$

Here the lightest color singlet is the $D_s^- N$ system at 2907 MeV. The CH contribution to the mass splitting $M(D_s^-p) - M(P^0)$ is the same as for the H particle, again in simple models of the color hyperfine interaction. The anti-Pentaquarks are defined in a similar way and, in general, whatever will be said about the Pentaquarks will also hold true for the charge-conjugate particles.

The calculations of ref. [7] account for the $SU(3)_F$ breaking. It was shown that as the symmetry breaking increases, the P always retains a larger binding potential than the H and that the binding can be several tens of MeV. The total binding energy includes the internal kinetic energy. Because the c quark is massive, the kinetic energy in the P is smaller than in the H by about 15 MeV. This improves the prospects of the P to be bound.

More recently, Takeuchi, Nussinov and Kubodera [8] studied the effects on the Pentaquark and Hexaquark systems of instanton induced repulsive interactions for three quarks in flavor antisymmetric states. They claim in this framework that both Pentaquark and Hexaquark are not likely to be bound. Also, Zouzou and Richard [6] reconsidered previous bag model calculations for the tetraquark and pentaquark. Their new calculation has weaker chromomagnetic attractions at short distances and a larger bag radius for multiquark states compared to ordinary hadrons. They find that the Pentaquark is unbound by 80 MeV, while the \tilde{F} tetraquark is unbound by 230 MeV. Similar conclusions for the P and H were given by Fleck *et al.* [7]. Riska and Scoccola [9] recently described the Pentaquark in a soliton model, using different parameter sets. One set gives a bound state, while another gives a near threshold resonance. Considering all the uncertainties in knowing the Pentaquark binding energy, our experimental approach is to search for both strongly and weakly bound Pentaquarks, as well as unbound Pentaquark resonances.

A very weakly bound D_s^-p deuteron-size bound state just below threshold with a structure very different from that of the strongly bound proton size Pentaquark might still be consistent with these recent calculations, considering all the model uncertainties. The D_s^-p system does not have Pauli blocking and repulsive quark exchange interactions which arise in all hadron-hadron systems where quarks of the same flavor appear in both hadrons. Thus, even a comparatively weak short range interaction could produce a relatively large size bound state analogous to the deuteron, with a long D_s^-p tail in its wave function and a good coupling to the D_s^-p system. The attraction is due to a short range interaction, not long-range one-pion exchange. This long attractive tail will also assist in the production mechanism. Because in the Pentaquark, unlike the deuteron, there is no short range repulsion, its structure at short distances will be quite different from that of the deuteron. This component too has its influence on the production mechanism. These issues are discussed in subsection 4.2. The deuteron-like state will be stable against strong and electromagnetic decays. Since the D_s^-p pair is some 50-75 MeV lower mass than other meson-baryon cluster components in the Pentaquark, it will be the dominant component in a weakly bound deuteron-like Pentaquark.

3 Structure and Decay Modes of the Pentaquark

There are different possibilities for the internal structure of observable (not very broad) exotic hadrons. They can be bound states or near threshold resonance structures of known color singlet sub-systems ($\Lambda\Lambda$ for the H [10] or $D_s^- p$ for the P^0). But they can have more complicated internal color structure; such as baryons with color octet and sextet bonds $[(qqq)_{8c} \times (q\bar{q})_{8c}]$ and $[(qq\bar{q})_{\bar{6}c} \times (qq)_{6c}]$ (see ref. [11]). We designate all such structures as direct five quark configurations. If color substructures are separated in space by centrifugal barriers, then exotic hadron resonances can have not very large or even anomalously narrow decay widths, because of complicated quark rearrangements in the decay processes. If these exotic hadrons are bound strongly, they can be quasistable, with only weak decays.

The wave function of the Pentaquark contains two-particle cluster components, each corresponding to a pair of known color singlet particles; and also a direct five quark [non-cluster] component. The Pentaquark production mechanism and its decay modes depend on these components. The P^0 can be formed for example by the coalescence of $pD_s^-, \Lambda\bar{D}^0, pD_s^{*-}, \Sigma^+ D^- + \Sigma^0 \bar{D}^0, \Lambda\bar{D}^{*0}, \Sigma^+ D^{*-} + \Sigma^0 \bar{D}^{*0}$; or by a one-step hadronization process. Let us consider three color-singlet components of the $P^0 : D_s^- p$ (2907 MeV), $D^- \Sigma^+$ (3058 MeV) and $\bar{D}^0 \Lambda$ (2981 MeV). The relative strengths of these components depend strongly on the binding energy, as discussed above for the deuteron-like Pentaquark. Pentaquark searches in progress in E791 [12, 13] are based on charged particle decay modes of different Pentaquark components: $D_s^- p \rightarrow \phi \pi^- p$ (B=3%), $D_s^- p \rightarrow K^{*0} K^- p$ (B=3%), $D^- \Lambda \rightarrow K^+ \pi^- \pi^- \Lambda$ (B=8%), $\bar{D}^0 \Lambda \rightarrow K^- \pi^+ \Lambda$ (B=4%) and $\bar{D}^0 \Lambda \rightarrow K^- \pi^+ \pi^+ \pi^- \Lambda$ (B=8%). The indicated branching ratios are those of the on-shell D-meson. Weak decays of virtual color singlet substructures in bound states are possible, ΛD^0 or $\Sigma^+ D^-$ for example, if their masses are smaller than the $D_s^- p$ threshold. In other cases, there would be strong decays through quark rearrangement $(\Sigma^+ D^-)_{bound} \rightarrow D_s^- + p$, and so on. Even if the masses are smaller, the phase space favors decay to the lightest system. The phase space factor would cause the partial width for any decay mode to be smaller than for the on-shell decay, making the total lifetime longer.

The decay through the direct five quark [non-cluster] component can open many additional channels; such as two-particle $\pi^- p$, $K^- p$, and $\Xi^- K^+$ final states. These additional decay modes can shorten the lifetime of the Pentaquark, which would reduce the experimental possibilities to observe it. Such relatively simple final states are more prone to contamination by large combinatoric backgrounds.

Consider the resonant Pentaquark possibility. Yields can be high, as one measures the total strong decay, rather than a particular weak decay mode. The width is the crucial parameter that determines the possibility to observe a resonance. Chances for observation would be good if it is of the order of 50-100 MeV or lower, similar to widths of excited D^* mesons and widths estimated by Greenberg and Lomon [14] for the lowest lying strangeness -1 dibaryon resonances. Our attitude is to support experimental searches for narrow exotic Pentaquark resonances.

4 Experimental Pentaquark Search

An experimental program to search for the Pentaquark should include:

- (1) Reactions likely to produce the Pentaquark, complemented by an estimate of the production cross section.
- (2) Experimental signatures that allow identification of the Pentaquark.
- (3) Experiments in which the backgrounds are minimized.

These points will be further discussed in the following subsections.

4.1 Experimental Considerations

All charm experiments require vertex detectors consisting of many planes of silicon micro-strips with thousands of channels. E791 used 23 such planes. Some of the planes are upstream of the target. These detectors allow a high efficiency and high resolution for reconstruction of both primary (production) vertex

and secondary (decay) vertex. The position resolution of the vertex detectors is typically better than 300 microns in the beam direction. By measuring the yield of a particle as a function of the separation between the two vertices, the lifetime of the particle is obtained. Other major components of the spectrometers are dipole magnets for momentum analysis, wire chambers for track reconstruction, cerenkov counters for particle identification, and Electromagnetic and Hadronic calorimeters. Muon detectors are included for studies of leptonic decays. The invariant mass resolution for typical charm masses in such spectrometers is about 10 MeV. Different spectrometers are sensitive to different regions of Feynman-x values.

In hadronic production, the charm states produced are preponderantly charm mesons at low x. The triggers for such experiments vary. In E791, the requirement was to ensure an interaction in the target (using signals from various scintillators) and a transverse energy (E_t) larger than some threshold. The rest of the charm selection was done off-line. Increased charm sensitivity can be achieved as in E781 [15] by a trigger condition that identifies a secondary vertex. A good charm trigger can produce an enriched sample of high x charm baryons with improved reconstruction probability because of kinematic focusing and lessened multiple scattering. Charm2000 experiments will also require charm enhancement triggers [16]. The present E791 and future E781 and Charm2000 experiments [17] complement each other in their emphasis on different x regions, incident particle types, statistics and time schedules.

4.2 Pentaquark Production Mechanisms

We consider possible mechanisms for P formation. For the central hadron-nucleus charm production at several hundred GeV/c, the elementary process is often associated with $q\bar{q} \rightarrow c\bar{c}$ or $gg \rightarrow c\bar{c}$ transitions. The produced charmed quarks propagate and form mini-jets as they lose energy. Hadronization associated with each jet proceeds inside the nucleus, and to some extent also outside the nucleus; depending on the transverse momentum of the jet. The propagating charmed quarks may lose energy via gluon bremsstrahlung or through color tube formation in a string model, or by other mechanisms, as discussed in ref. [18] and references therein. One may form a meson, baryon, Pentaquark, according to the probability for the charmed quarks to join together with appropriate quarks and antiquarks in the developing color field. One can estimate Pentaquark production cross sections via one-step and also two-step hadronization. All such estimates are very rough. Our aim is to account for major ingredients in estimating the cross section, and to give a conservative range of values. For one-step hadronization, the \bar{c} joins directly to the other quarks. The one-step is the usual mechanism for meson and baryon formation. For two-step, the first involves meson and baryon hadronization, while the second involves meson-baryon coalescence.

We first consider estimates for the central production cross section assuming a meson-baryon coalescence mechanism, expected to be the main mechanism for production through the long-range (deuteron-like) component of the Pentaquark wave function. We make a crude estimate relative to the D_s^- , an anticharmed-strange meson ($\bar{c}s$). The weakly bound P (deuteron type structure) can be produced by coalescence of a proton or a neutron with a D_s^- , analogous to the production of a deuteron by coalescence of a neutron and a proton. The data [19] give roughly 10^{-3} for the $\sigma(d)/\sigma(p)$ production ratio. This ratio can also be applied to $\sigma(P)/\sigma(D_s^-)$ production. The reason is that in both cases, the same mass (nucleon mass) is added to the reference particle (proton or D_s^-), in order to form a weakly bound deuteron-like state.

We now consider the one-step hadronization of a Pentaquark, expected to be the main mechanism for the production through the short-range component of the Pentaquark wave function. We rely here on an empirical formula which reasonably describes the production cross section of a mass M hadron in central collisions. The transverse momentum distribution at not too large p_t follows a form given as [20]:

$$d\sigma/dp_t^2 \sim \exp(-B\sqrt{M^2 + p_t^2}), \quad (4)$$

where B is roughly a universal constant $\sim 5 - 6 \text{ (GeV)}^{-1}$. The exponential fit has inspired speculation that particle production is thermal, at a temperature $B^{-1} \sim 200 \text{ MeV}$ [20]. One can also include a $(2J+1)$ statistical factor to account for the spin of the hadron. To illustrate the universality of B, we evaluate it for a few cases. For Λ_c and Ξ^0 , empirical fits to data give $\exp(-bp_t^2)$, with $b=1.1 \text{ GeV}^{-2}$ and $b=2.0 \text{ GeV}^{-2}$, respectively [21, 22]. This corresponds to $B= 5.0 \text{ GeV}^{-1}$ for Λ_c , and $B= 5.3 \text{ GeV}^{-1}$ for Ξ^0 . For inclusive

pion production, experiment gives $\exp(-bp_t)$ with $b = 6 \text{ GeV}^{-1}$ [23]; and $B \sim b$, since the pion mass is small. Therefore, $B = 5\text{-}6 \text{ GeV}^{-1}$ is valid for Λ_c , Ξ^0 hyperon, and pion production. We expect therefore that eq. 4 should be also applicable to Pentaquark production. After integrating over p_t^2 , we estimate the ratio:

$$\sigma(P)/\sigma(D_s^-) \sim \exp[-5[M(P) - M(D_s^-)]] \sim 10^{-2}. \quad (5)$$

For illustration, let us consider the ratio of Λ_c to D_s^- total production cross sections by sufficiently energetic baryon beams. This ratio is roughly 0.23, comparing the Λ_c cross section [21] with incident Σ^- to the D_s^- cross section [25] with incident neutron. Eq. 5 with the masses of these particles, including a spin statistical factor, gives about the same ratio. In applying eq. 5 to Pentaquark production, we assume that the suppression of cross section for the heavy P as compared to the light D_s^- is due to the increased mass of P. The particular one-step hadronization process is not relevant. However, as the size of the P increases, this formula would be less and less reliable. Cross section estimates for P production have been given previously [12, 13], based on other arguments, and are consistent with the ratio given by eq. 5.

All the various reaction mechanisms described above can contribute to the production cross section, which is estimated in the range of $\sigma(P)/\sigma(D_s^-) = 10^{-3} - 10^{-2}$. In actual measurements, the product $\sigma \cdot B$ for a particular decay mode is measured, and estimates of the P lifetime and branching ratios may be necessary as well.

4.3 Pentaquark Expected Yield

We proceed with count rate estimates. Analysis of a part of the E791 data (500 GeV/c π^- beam) already yielded a preliminary upper limit $\sigma(P^0)/\sigma(D_s^-) < 6\%$ for Pentaquark production [24]. This was done for the $D_s^- \rightarrow \phi\pi^-$ and $P^0 \rightarrow \phi\pi^-p$ decays assuming the same branching ratios. It was based on a small fraction of the data and measured D_s^- yield. With the full data sample, several tens of Pentaquarks may be observed if the cross section is in the range estimated in the previous section. For the planned E781 and charm2000, when both use Baryon beams, we rely on previous measurements done with similar beams. With 600 GeV/c neutrons, the D_s^- was measured [25] in the $D_s^- \rightarrow \phi\pi^-$ decay mode with $\sigma_B = 0.76 \mu\text{b}/\text{N}$ for $0.05 < x < 0.3$, where x designates the Feynman x -value. For Baryon beams the cross section should be proportional to $(1-x)^n$, with n between 4.5 and 5.5, based on the WA89 experiment [21] with a 300 GeV/c Σ^- beam. These data and x -dependence correspond to $\sigma \cdot B$ values for the whole range of $x > 0$ of roughly $1 \mu\text{b}/\text{nucleon}$. With the $\sigma(P)/\sigma(D_s^-)$ factors given above, we estimate $\sigma \cdot B = 1 - 10 \text{ nb}/\text{N}$, for each of P^0 and P^- . For E781, scheduled for 1996, the experimental conditions should allow reconstructed Pentaquark events at a rate of roughly 200 events/nb. These expectations are based on a contribution to this workshop by J. Russ [15], which cites an expected yield of 2300 charm events/nb of cross section for 100% efficiency. The efficiencies include a tracking efficiency of 96% per track, a trigger efficiency averaged over x of roughly 18%, and a signal reconstruction efficiency of roughly 50%. We therefore assume an overall average Pentaquark reconstruction efficiency of $\varepsilon \simeq 8\%$. We then estimate an expected yield of $N(P^0) = 200 - 2000$ in E781. If we assume a rate of 2000 events/nb for charm2000, the Pentaquark yield may reach the 2000 - 20,000 range. These projections depend critically on the value used for the D_s production cross section. We note that the value quoted in [25] is exceptionally large.

It is still possible that different mechanisms for charm production contribute in different x regimes. For example, there is evidence for leading production of charmed hadrons in WA89 and FNAL E769 [26], which suggests diffractive contributions. For charm2000, one could study [10] the pair diffractive production reaction $p + N \rightarrow (P^0 D_s^+) + N$, with possible D_s^+ tag or without such tag. For the diffractive pair production cross section, one can compare to the diffractive cross section for the reaction $p + N \rightarrow (\Lambda K^+) + N$ at 70 GeV; about $4 \mu\text{b}$ after subtraction of isobar contributions [27]. Estimates are needed but are not available for the cross section ratio $\sigma(P^0 D_s^+)/\sigma(\Lambda K^+)$. For the ratio of 10^{-3} , with $B = 3\%$, one would obtain around 240 reconstructed P^0 baryons with charm2000. There is the D_s^+ tag possibility for this process. The efficiency for tagged versus untagged events is reduced, but tagging may improve the signal to background ratio.

4.4 Pentaquark Decay Signatures

(1) Mass and Width and Decay Modes:

Searches for the Pentaquark are easiest via modes having all final decay particles charged. With all charged particles detected, the invariant mass of the system can be determined with high resolution. One signature of the Pentaquark is a peak in the invariant mass spectrum somewhat lower than 2907 MeV if the system is bound, and above if it is a resonance. The position of the peak should be the same for several decay modes. It's width should be determined by the experimental resolution if it is bound, and broader if it is a resonance.

The selection of the decay modes to be studied is made primarily by considering detection efficiency and expected branching ratios. Since the $D_s^- p$ system is the lightest it is expected to be preferred from phase space arguments. Also, two of its decay modes have four charged particles in the final state (e.g. $K^+ K^- \pi^- p$: $\phi \rightarrow K^+ K^-$, $K^* \rightarrow K^+ \pi^-$). We describe how this signature is implemented. First, two distinct vertices are identified: a production vertex and a decay vertex. From the decay vertex, four tracks are identified and associated with $K^+ K^- \pi^- p$. By reconstructing the invariant mass of the $K^+ K^-$ pair, one can require only ϕ mass events. One then reconstructs the invariant mass of all four particles. If there is a peak in the resulting spectrum, it will be one of the identifying characteristics of the Pentaquark. One can also study a strong decay into $D_s^- p$, if the P is a resonance. For this strong decay, the proton and D_s^- come from primary vertex, and the D_s^- decay forms the secondary vertex. Both weak and strong decay modes coming from the $D_s^- p$ and the $\bar{D}^0 \Lambda$ components of the P are currently being studied in E791.

(2) One General Signature - A Spectator Baryon:

We first note a striking signature for Pentaquark decay which may be useful for discrimination against background. This signature is predicted by both of two very different Pentaquark models (1) a loosely-bound $D_s^- p$ deuteron-like state and (2) a strongly-bound five-quark state. Both models predict decay modes into a baryon and two or more mesons, in which the three quarks in the baryon are spectators in the decay process and remain in the final state with a low momentum which is just the fermi momentum of the initial bound state.

That the baryon is a spectator is obvious in the deuteron model, in which the decay is described as an off-shell D_s^- decaying with a nucleon spectator. In the five-quark model, a similar situation arises in the commonly used spectator model with factorization. Here, the charmed antiquark decays into a strange antiquark by emission of a W^- which then creates a quark-antiquark, which hadronizes into mesons. The strange antiquark combines with one of the four spectator quarks to form one or more mesons, while the three remaining spectator quarks combine into a baryon.

In both cases, it seems that the final state should show a low-momentum baryon in the center-of-mass system of the Pentaquark and the invariant mass spectrum of the remaining mesons peaked at the high end near the kinematic limit. Thus in the particular cases of the $p\phi\pi^-$, $K^{*0}K^-p$ and $\Lambda K^+\pi^-$ decay modes, the $\phi\pi^-$, $K^{*0}K^-$ and $K^+\pi^-$ invariant mass distributions respectively should show this peaking near the kinematic limit.

Note that in the particular case of the $p\phi\pi^-$ decay mode, a low momentum proton in the center of mass system means that the π^- and ϕ are back to back with the same momentum and therefore that the pion carries off most of the available energy. Thus one might reduce background with a cut that eliminates all pions with low momentum in the center of mass.

(3) Some Model-Dependent Branching Ratio Predictions:

The $\phi\pi^-p$ decay mode is the most convenient for a search, since the ϕ signal is so striking. We now examine the lowest order predictions from the two extreme models for the branching ratios of other modes relative to $\phi\pi^-p$.

In experiments sensitive only to charged particles the $\phi\pi^-p$ decay mode is observed in the four-prong final state $K^+K^-\pi^-p$. The $K^{*0}K^-p$ decay mode is also observable in this same four prong final state. The $K^{*0}K^-p$ decay mode arises naturally in the deuteron model, since the $K^{*0}K^-$ decay is observed for D_s^- decays with a comparable branching ratio to $\phi\pi^-$. In this model, the ratio of the two decays is predicted from observed D_s^- decay branching ratios with phase space corrections. However, the $K^{*0}K^-p$ decay mode does not occur in the five quark spectator model, where the spectator strange quark can only combine with the \bar{s} produced by the charm decay to make a ϕ or with two spectator nonstrange quarks to make a hyperon. Comparing the two decays thus tests the decay model.

The $K\pi\Lambda$ and $K^*\pi\Lambda$ decay modes arise naturally in the five quark spectator model. However, they should not be expected in a very weakly bound deuteron model with mainly a $D_s^- p$ structure. In that case, the D_s^- decays into mesons containing one strange quark-antiquark pair and the baryon spectator has no strangeness.

(4) Angular Momentum Constraints and Angular Distributions for P Decays:

We can give a model-independent prediction. The Pentaquark has spin 1/2 and this total angular momentum is conserved in the decay. Since the production process is a strong interaction which conserves parity, the Pentaquark will not be produced with longitudinal polarization. Its polarization in the beam direction must also vanish. Therefore, the angular distribution in the center-of-mass system of the Pentaquark must therefore be isotropic for the momentum of any final state particle in any decay mode with respect to either the incident beam direction or the direction of the total momentum of the Pentaquark. The background does not necessarily have these constraints.

We also give a model-dependent prediction. We first consider the deuteron model. The D_s^- has spin zero, and spin is preserved in the decay. Thus, in the center of mass frame of all the D_s^- decay products,

the angle between the proton momentum and the momentum of any particle emitted in the D_s^- decay must have an isotropic angular distribution.

A further prediction is obtainable for the case of a vector-pseudoscalar decay mode of the D_s^- ; e.g. $\phi\pi^-$ or $K^{*0}K^-$. The vector meson must be emitted with zero helicity in the rest frame of the D_s^- . The zero helicity can be seen in the $\phi\pi$ decay by measuring the angle $\theta_{K\pi}$ between the kaon momenta in the ϕ rest frame and the pion momentum. The prediction is to have a $\cos^2 \theta_{K\pi}$ distribution. By contrast, the five-quark model for the Pentaquark favors helicity one over helicity zero for the vector meson by just the 2:1 ratio needed to give an isotropic distribution in $\theta_{K\pi}$. Here again the background does not necessarily have these constraints.

4.5 Reducing Background

There is much background from central interactions. When low x production is studied, the momenta of P^0 decay products are also lower. As a result, the background rate increases faster than the charm signal. It is known [27] that the combinatoric background in inclusive processes is significantly reduced in the fragmentation region ($x \geq 0.6$). The produced particles and the decay fragments from the P , especially for high- x production, are all focused in a forward cone in the laboratory system. One has therefore a good efficiency for detecting all particles in the final state. The diffractive pair production reactions with low combinatoric background also contribute in this high x region. One would expect more favorable background conditions at high x for the identification of resonance P baryon states.

High quality particle identification (PID) for the largest possible energy range of the outgoing particles is important for reducing backgrounds associated with incorrect identification of tracks. This is available in E781, for example, via ring imaging Cerenkov (RICH) and transition radiation detector (TRD) PID systems. The separation of vertices is very important also for reducing the combinatoric backgrounds, as the majority of particles come from the primary vertex. These and other experimental techniques to reduce backgrounds are described in more detail in the contribution of J. Russ [15].

5 Heavy Baryons with Hidden Charm

In recent years, several candidates were reported for baryon states with unusual properties (narrow decay widths, large branching ratios for the decays with strange particles). There are candidates for cryptoexotic baryons with hidden strangeness $B_\phi = |qqqs\bar{s}\rangle$ ($q = u$ or d quarks) [28]. Although the existence of such a baryon is not yet confirmed [29], the suggestions raise the question of the possible existence of heavy cryptoexotic baryons with hidden charm $B_\psi = |qqqc\bar{c}\rangle$. If $M(B_\psi) < M(\eta_c) + M(p) \simeq 3.9$ GeV, the B_ψ decays would be OZI suppressed and the width of this cryptoexotic baryon would be quite narrow (≤ 1 MeV). To search for such B_ψ states, it was proposed [30] to use the diffractive production reaction $p + N \rightarrow B_\psi^+ + N$; with possible decays of B_ψ baryons $B_\psi^+ \rightarrow p + (J/\psi)_{virt} \rightarrow p + (l^+l^-)$ or $B_\psi \rightarrow p + (\eta_c)_{virt} \rightarrow p + (K^+K^-\pi^+\pi^-; 2\pi^+2\pi^-; K\bar{K}\pi; \eta\pi\pi)$. The $\sigma \cdot B$ was estimated as roughly 1.5 nb [30]. Assuming the expected Charm2000 efficiency of 2000 events/nb would hold for these events too, this would correspond to the detection of roughly 3000 events.

If $M(B_\psi) > 4.3$ GeV, there would be OZI allowed decays $B_\psi^+ \rightarrow p + J/\psi; \Lambda_C + D^0$, etc. Because of a complicated internal color structure of this baryon (see Introduction), one expects a narrow decay width (≤ 100 MeV). Such resonance states may be observable in diffractive production reactions.

6 Conclusions

We described the expected properties of Pentaquarks. Possibilities for enhancing the signal over background in Pentaquark searches were investigated. General model-independent predictions were presented as well as those from two models: a loosely bound $D_s^- N$ "deuteron" and a strongly-bound five-quark model. While the current E791 may have marginal sensitivity, future experiments with more than 10^5 reconstructed charmed baryon events should have sensitivity to determine whether or not the Pentaquark exists.

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